A SPATIALLY EXPLICIT STREAM AND OCEAN NETWORK USED TO MODEL HABITAT-SALMON INTERACTIONS

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ABSTRACT

Williams, I.V., T.J. Brown, M. McAllister, and D. Hawkins. A spatially explicit stream and ocean network used to model habitat-salmon interactions. Can. Tech. Rep. Fish. Aquat. Sci. 2298: 28 p.

A spatially explicit stream network was built for the major salmon spawning streams within the Fraser River Basin in British Columbia using digital data from the Terrain Resource Information Management (TRIM) maps. Several models were built to aid in the construction of a seamless network spanning approximately 1750, 1:20,000 digital maps. A center line used for migration was calculated from the right and left banks of the rivers as well as through lakes. Tributary streams connect to the center line providing a simple network for modelling various aspects of salmon life histories and salmon habitats. Examples of migration paths, spawning, rearing areas, and linking terrestrial drainage paths to stream networks are presented.

RÉSUMÉ

Williams, I.V., T.J. Brown, M. McAllister, and D. Hawkins. A spatially explicit stream and ocean network used to model habitat-salmon interactions. Can. Tech. Rep. Fish. Aquat. Sci. 2298: 28 p.

Nous avons établi un réseau spatialement explicite représentant les principaux cours d'eau de fraye du saumon dans le bassin du fleuve Fraser, en Colombie-Britannique, à l'aide de données numériques tirées des cartes TRIM (Terrain Ressource Information Management). Plusieurs modèles ont été conçus pour aider à établir un réseau continu couvert par approximativement 1 750 cartes numériques au 1:20 000. Une ligne médiane utilisée pour la migration a été établie à mi-chemin entre les rives droite et gauche des cours d'eau et au centre des lacs. Les affluents sont reliés à cette ligne médiane, ce qui constitue un réseau simple permettant de modéliser divers aspects du cycle biologique du saumon et de ses habitats. Le document présente des exemples de voies migratoires, d'aires de fraye et de grossissement, et fait des liens entre les voies d'écoulement terrestre et les réseaux de cours d'eau.

1. INTRODUCTION

Recent developments in information systems and spatial analysis have provided tools for analyzing and integrating salmon habitat information with salmon stock data. There has been a cooperative effort between the B.C. Ministry of Environment, Lands & Parks (MELP) and the Federal Department of Fisheries and Oceans Habitat and Enhancement Branch (HEB) to inventory fish habitat, including data gathered with the help of volunteer groups (Brad Mason, Fisheries and Oceans Canada, Vancouver, pers. com.). These data are archived in the Fish Inventory Summary System (FISS) database and descriptions are available on the internet (http://habitat.pac.dfo.ca/heb/fhiip/reportsi.htm). In addition, a new generation of digital base maps, Terrain Resource Information Management System (TRIM) at a scale of 1:20,000, is under development for British Columbia. These data, combined with the power of GIS spatial analysis systems and applications, provide powerful tools for scientists and resource managers. The task of applying information in a meaningful way in order to execute knowledge-based resource management in a rapidly changing environment remains a challenge. For salmon, this means understanding the role of salmon in the ecosystem, the effect of natural and anthropogenic-induced change on the production of salmon, and the role of salmon in society.

Salmon are central to a very complex ecosystem, spanning fresh and salt water. They contribute to the well being of a myriad of life forms, from vegetation through the transport of micronutrients, to other vertebrates as a food source, including man. Salmon are an important part of the socio-economic base of British Columbia and will continue to be as long as the resource is managed with foresight and wisdom. As society advances, complexity in resource management increases. Tools that provided excellent support in the past are not adequate for today's complexity (e.g. Ricker curves for managing fish populations and 1-mile buffer strips used in the upper Fraser Basin for managing fish habitat). There are many tools in use today that are designed for a specific location and a specific purpose (e.g. PHABSIM/IFIM, Bovee, 1982). There are also overviews of salmon productivity; some focus on watersheds while others relate to ocean events and climate (Stalnaker et al. 1989, Stroud 1992, Walters and Ward 1998). Good resource management requires tools capable of dealing with complex decisions on a part of the whole, within the context of the whole. Ideally, these tools incorporate data and knowledge from a wide variety of sources (land, fresh water, and oceans), integrate these into a comprehensive and cohesive information system, incorporate our current understanding of ecosystem processes, and simplify the complexity of the system without losing the detail required for good management decisions. There are currently several such systems under construction (Lestelle et al. 1996).

This report describes the components of the Integrated Fraser Salmon Model (IFSaM) migration networks, which is one of a suite of tools for salmon management (Williams et al. 1996). The IFSaM combines the knowledge of ocean and freshwater habitat with the knowledge of salmon population dynamics to enhance our understanding of processes involved in salmon production. One of the main purposes of IFSaM is to simplify data organization and integrate knowledge with models, both present and future, in a common base or platform. We believe that a spatially explicit river network based on TRIM data is the best available platform to integrate data, knowledge, and models, as well as to develop new models to enhance our understanding of cumulative environmental and anthropogenic effects on salmon.

Section 2 describes the software and data resources upon which IFSaM migration networks are built. Section 3 presents the components of IFSaM migration networks.

2. IFSaM RESOURCES

Since IFSaM is designed to be a common platform for developing current and future models, the software upon which it is based must be convenient for creating models, accessible to experts and non-experts alike, and able to use a variety of data sources. We use the Cause & Effect (C&E) software of Facet Decision Systems Inc. of Vancouver B.C. for this purpose. Section 2.1 presents a brief overview of the C&E software.

The data that unifies the models in IFSaM must be available at a common minimum level of resolution for all areas of British Columbia. We chose TRIM data as the source of data for building the stream networks for IFSaM. The 1:20,000 scale was seen as an advantage over the available 1:50,000 data, both for retrieval of data for visual display and for modeling events and processes. Section 2.2 presents the characteristics of TRIM data that are relevant to IFSaM.

2.1. Software Environment: Cause & Effect

C&E is a decision support package and its primary interface is a spreadsheet-like browser in which users can build powerful and complex models. Through the browser, the user can import and export data to and from many standard file formats and can issue sequential query language (SQL) queries to external databases. C&E can display graphical results in a visualization environment for 3D data called the "Visualizer". Since the start of the IFSaM project, C&E has added the ability to export results in postscript files for printers and to present 2D data with a java interface. The browser interface allows the user to import data into cells and then invoke mathematical, list, raster, or vector functions to transform and analyze the data (Facet 1998).

Lists and features are the standard data types in C&E. Lists represent tables of attributes or collections of related data. Lists can consist of integers, floating-point numbers, boolean values, strings, points, features, or other lists. Features can be a set of points called polymarkers, a set of polygonal lines called polylines, or a set of polygons. Both polylines and polygons are simply sequences of points. With polylines, the important information is the sequence of points themselves. With polygons, the important information is the area enclosed by the polygonal boundary indicated by the sequence of points. However, users are not limited to only using lists and features; they can create their own data types based on the basic data types of integers, floating point numbers, boolean values, strings, points, features, and lists.

A strength of C&E is that the browser interface can be nested: a cell in one browser can contain a browser of its own, thus creating a hierarchy of interconnected browsers. A browser at one level in the hierarchy automatically has access to the data and functions defined in the higher level browsers. A browser can have access to the data and functions of lower level browsers by specifying the dot-separated sequence of browsers that lead through the hierarchy to the data, such as "browser1.browser2.browser3.routine". With this hierarchy, data and functions that embody one concept, such as a method for selecting map sheets, can be grouped in one browser at a different level of the hierarchy and do not clutter the cells of another browser that is creating a model. Moreover, concepts that are grouped into their own browsers can be read into other C&E models to re-use previous work.

Once a model is created in C&E, the user of the model may be different from the author of the model and may not need to deal with the generality of the browser interface. C&E has a point-and-click tool that assists a model author in creating a graphical user interface (GUI) to their model. The author can

have cells in the browser interface controlled by intuitive GUI objects such as push buttons, selection lists, and scroll bars. Non-expert users can then interact with the model strictly through the GUI.

C&E models are easy to transport and convenient to start. The models are stored as small text files, which allows a user to easily review, transport, or print the files. Data locations are identified in browser cells named "path", located near the upper left-hand corner. These path scripts, e.g. "/dfo/data/" are commonly changed when moving a model to another platform, as data are rarely stored in the same folder tree. Data are imported into the browser by appending a filename to the path and, if necessary, adding the name of an import filter, e.g. "import(path<<"filename", "filtername")". Models are usually accompanied with a script in the same directory as the model that loads the model and presents the user with either a browser interface or a GUI depending on the model's configuration. The starting script is conventionally named "GO".

No software package can guarantee that it contains all the functions that might be required for any future model. When there is a need for a function that does not appear in C&E, experienced users can create the function in C++ and load the function into C&E through Facet's developer software. Once loaded, the new functions are executed from the browser interface as easily as any built-in C&E function.

The Department of Fisheries and Oceans at Nanaimo operates C&E on a Sun Microsystems SPARC 20 workstation under the Solaris operating system.

2.2. TRIM Data

The British Columbia specification and guideline for geomatics (Ministry of Environment, Lands & Parks 1992) thoroughly describes the specifications for TRIM data. The important aspects for IFSaM are the accuracy and the geometric constraints. The TRIM specification demands a 10-metre accuracy in both x and y directions and a 5-metre accuracy in the z direction. For geometry, the TRIM specification states several constraints. First, when two lines meet, they meet at an endpoint of each line and the common endpoint has the same coordinates in both lines. Second, all rivers and riverbanks are digitized in a downstream direction. Third, all lakes and area-based features, like reservoirs, are digitized in a clockwise direction. Fourth, wide rivers that flow into a lake are separated from lakes by a pair of construction edges; the construction edges occur in opposite directions with one edge encoded as a lake edge and the other encoded as a river edge. These geometric constraints provide implicit information about the map items that are used in geometry-based algorithms, such as the river network construction algorithm.

TRIM maps are delivered in 5 binary files for different classifications of data. The file names encode both the location and the type of data. The location is a combination of the N.T.S. 1:250,000 map sheet designation and an identifier for the one of 100 grid cells at the 1:20,000 scale that form a grid within each N.T.S. 1:250,000 map sheet. Therefore, a map file name of 92G005 describes the map for the south arm of the Fraser River at the mouth.

The type of data is one of 5 letters appended to the location:

Code	Type of data
p	planimetric data
t	toponomy data
d	digital elevation data
g	raw contour data
n	non-positional data

Finally, all file names end with a ".bin" suffix. Therefore, the file 92G005p.bin contains the planimetric data for map 92G005 while the file 92G005d.bin contains the digital elevation data for the same map. The primary improvement of 1:20,000 TRIM data over 1:50,000 data is the presence of right and left banks for medium sized streams. We can model these streams in a spatially explicit model and attach small-scale attributes or model map data to the banks for complex analysis. This scale is not considered to be the scale of the final product for analysis but rather a spatially explicit base upon which finer detail can be appended if necessary. For example, we compared a digital 1:5,000 map produced by Timber West for the upper Comox Valley on Vancouver Island, with TRIM sheet data for the same area and found approximately 30% of stream length in the 1:5,000 data are missing in TRIM. In this case, the difference was seen in the higher slope classes (>0.01) in the headwaters of the tributaries (Fig. 1). In a field study of the Black Creek watershed on Vancouver Island, B.C., TRIM data delineated 73% of the total natural channel identified by ground surveys (Brown et al. 1996). The missing streams, in this case, are small tributaries, especially in areas of little relief, many of which are typical of coho habitat. These small watercourses can easily be added to models where appropriate.

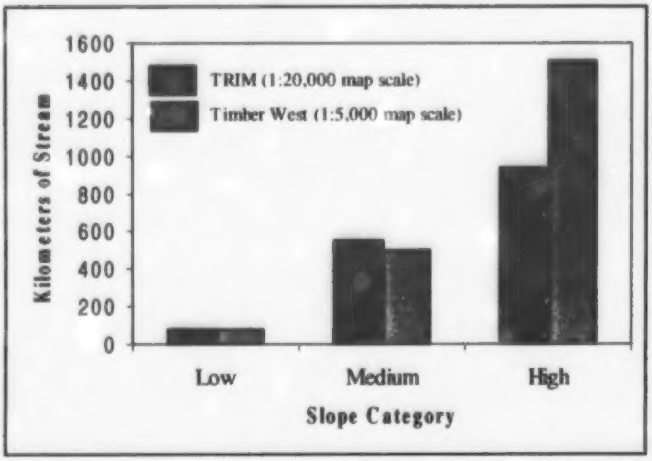


Figure 1. Comparison of stream length from a 1:5,000 digital map and TRIM data for the same area.

3.0. IFSaM COMPONENTS

We developed several models in C&E to build a seamless "intelligent" network with links to migration paths as well as to the land. These models were constructed in collaboration with Facet Decision Systems Inc., the Computer Science Department at the University of B.C., and the Department of Fisheries and Oceans Science Branch. IFSaM migration networks are built around three models: a TRIM key map model, a TRIM viewer model, and a network construction model. The following subsections provide details about each of these models.

3.1. TRIM Key Map Model

The IFSaM project requires over 1700 TRIM maps to cover all the streams in the Fraser River Basin. Since maps were acquired over an 18-month period, we constructed a model to track availability of map sheets, called the TRIM key map model. The model overlays a grid of TRIM map sheets for the

province of B.C. with a visual display of the map sheets that are resident on the workstation (Fig. 2).

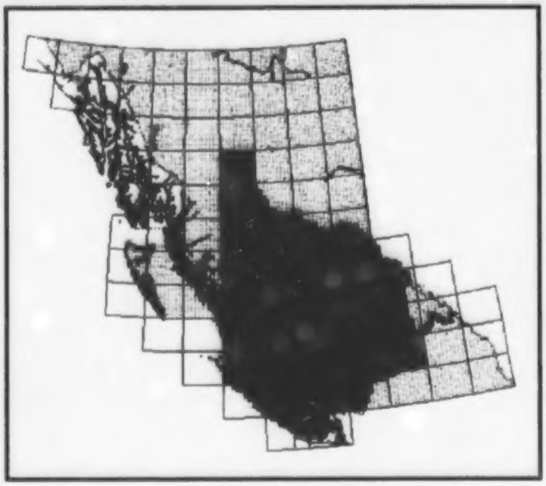


Figure 2. IFSaM key map used to track availability of TRIM map sheets

To create the overlay display, the model queries the map folders on the workstation, builds a list of maps based on their names, and displays the data as a map. The base map of the whole province is from a 1:1,000,000 scale map with the TRIM map sheet grid outlined in green. The available TRIM sheets appear as solid red squares. Fraser River Basin Habitat Management Areas are used to display the watershed.

This model was particularly useful for setting priorities for map acquisition by tracking maps that were available and those that were missing from our project.

3.2. TRIM Viewer Model

The TRIM viewer model displays TRIM maps in a C&E Visualizer and allows the user to select which attributes to show. A graphical user interface (GUI) handles the selection of TRIM map and map attributes. The TRIM viewer is not completely automated; the user must activate the visualizer with the "View Mapsheet" button before a map can be displayed.

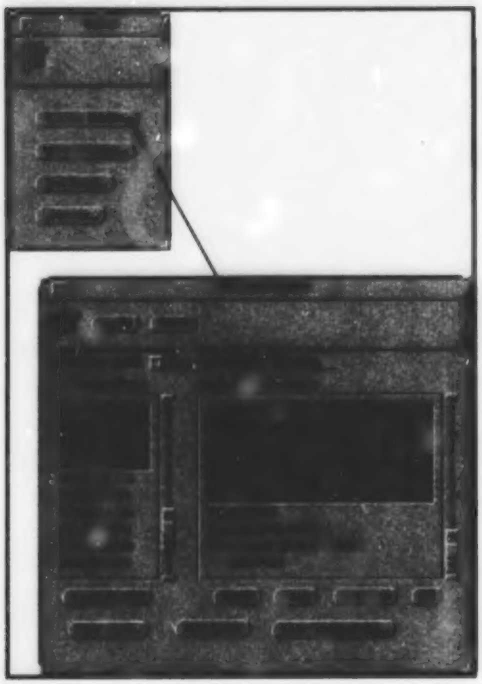


Figure 3. Graphical user interface for TRIM viewer model.

The GUI displays a list of available maps and their attributes (Fig. 3). Clicking the left mouse button on one or more map sheets in the list loads the map sheets into the model and converts the data into polymarker, polyline, or polygon features, as appropriate. The TRIM viewer then presents a viewable map (Fig. 4). The GUI automatically displays a list of attributes from the maps based on the 5 different TRIM file types. The user can now select attributes to display from this list with the right mouse button. The selected attributes only appear on the viewable map after the user clicks on the "Apply" button.

The first TRIM viewer only imported binary files. Given the large volume of data, the import filters in C&E were adapted to handle compressed binary files. Recent changes to C&E include an import filter for Spatial Archive and Interchange Format (SAIF) files.

3.3. Network Builder Models

The network builder model builds watersheds from digital TRIM data. We assign attributes to river line segments, which are represented by polyline features, to complete a

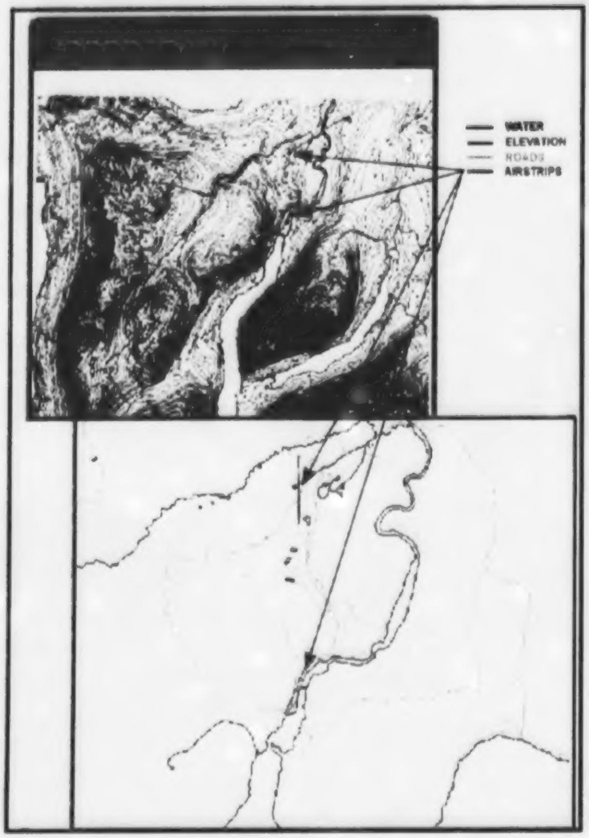


Figure 4. TRIM map display of Chilko Lake and River with several attributes selected.

watershed. The stream networks in the Fraser River Basin are based on the watersheds that support salmon spawning. For example, the Horsefly River has three tributaries that also support salmon spawning: McKinley, Moffat, and Little Horsefly River. Therefore, four networks describe the Horsefly watershed (Fig. 5).

The network builder is a more complex model than the TRIM key map model or the TRIM viewer model. The first network builder model was limited by inappropriate paths through lakes for fish migrations and led to the development of a second network builder model. Section 3.3.1 describes the overall process involved in creating a network with the network builder model. Section 3.3.2 describes the first network builder model and gives more details on its limitations. Section 3.3.3 describes a model that transfers the early work done in the first version of the network builder into a format that is used by the second network builder. Finally, Section 3.3.4 describes the second network builder model. All the network builder models use a GUI interface. There is no need to access the browser interface for these models, but the browser is available if the user desires to use it.

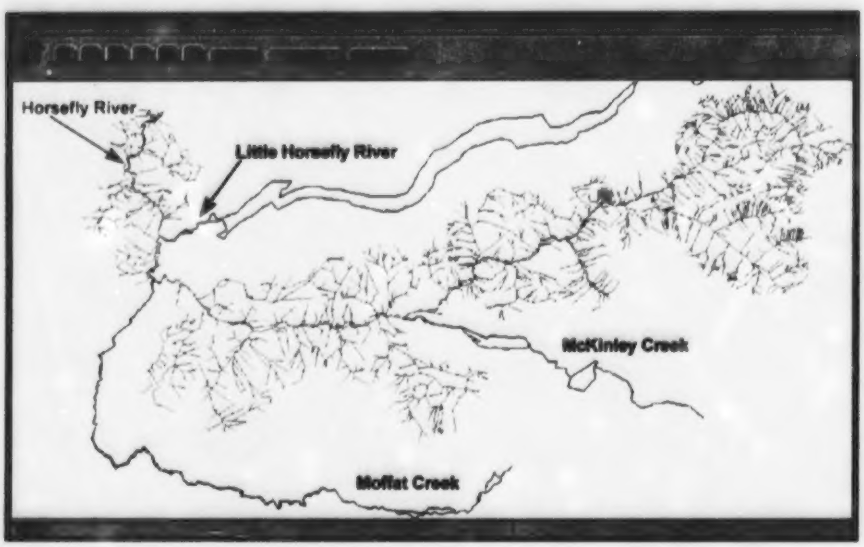


Figure 5. Horsefly River watershed with 3 salmon spawning tributaries displayed as mainlines only.

3.3.1. Network Creation Process

Networks are created on a watershed basis. We use 1:50,000 topological scale maps as a reference base when identifying the watersheds. For each watershed we identify the downstream and upstream limits of a mainstem. The upstream points of all tributaries are then located using these tools in an interactive process, essentially defining a watershed. If the tools include a tributary that belongs to a different watershed then the data for that tributary is removed. Once the rivers in the watershed form a seamless network that covers the watershed, the 2-line rivers and lakes are collapsed to a single line network that retains its association to the TRIM data and attributes. We can then join individual watersheds into a larger network, for example, a migration path for a sockeye stock group that uses multiple spawning streams in the Fraser Basin.

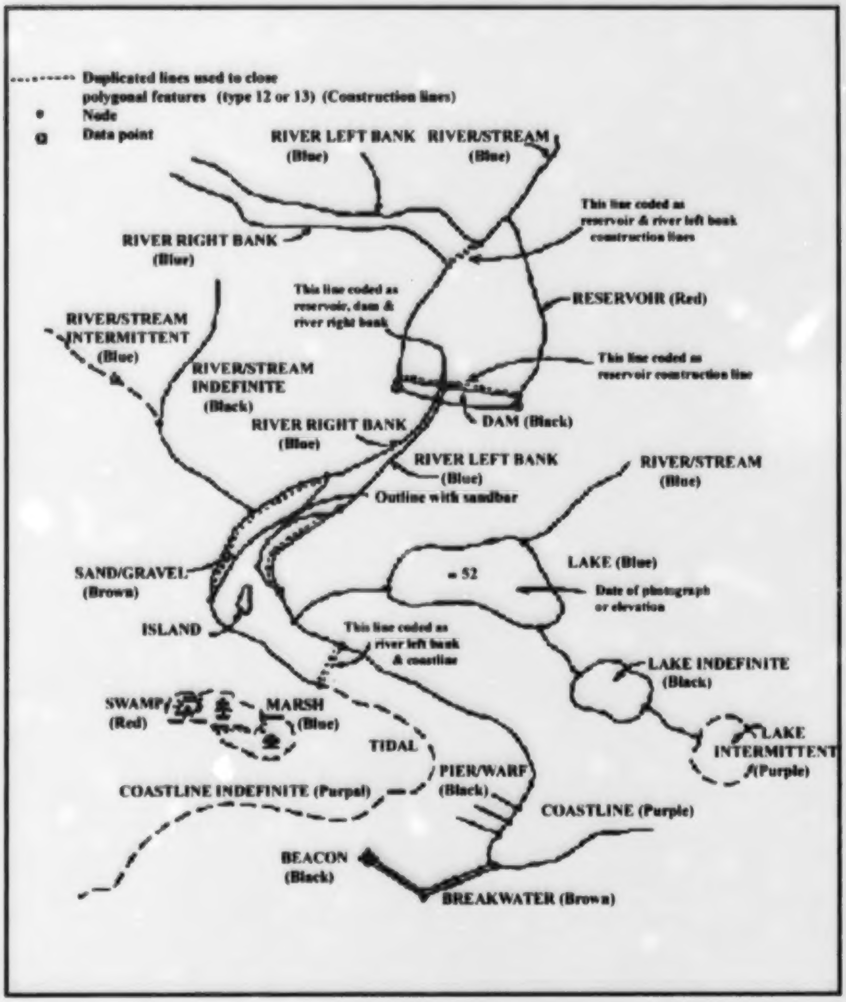


Figure 6. Diagram illustrating digitizing conventions for hydrographic and related features in TRIM maps (MELP 1992).

The first step in creating a network is to select the planimetric edges that will be used for building a watershed network. We select the edges from their TRIM attributes. When viewing TRIM map sheets, we display all the available edges, but we only use rivers, canals, reservoirs and lakes to build the stream network. The TRIM specification classifies these features into three types: definite, indefinite and intermittent (Fig. 6).

For modeling convenience, we re-classify the edges according to whether or not the watercourse has its banks digitized and whether or not a definite direction of flow exists along the edges. An integer attribute, called "kind", tracks the new classification in the network. Table 1 summarizes the new classification codes. It is important to understand that, for this project, no attempt was

made to integrate other features that would provide more detail. These include sandbars and islands within lakes and rivers. This information would be relatively easy to include if a project required this detail.

Table 1. TRIM feature codes

Type	TRIM Feature Code	KIND (Facet Code)
Single line river	GA24850000	1
River indefinite	GA24850140	1
River intermittent	GA24850150	1
Canal	GA03950000	1
Left bank of 2 line river	GA90000110	2
Left bank of canal	GA90001110	2
Right bank of 2 line river	GA90000120	3
Right bank of canal	GA90001120	3
Lake definite	GB15300000	4
Lake indefinite	GB15300130	4
Lake intermittent	GB15300140	4
Reservoir definite	GB24300000	4

The second step is to transform the planimetric TRIM data into a format that is easy to manipulate within C&E. C&E imports a binary TRIM file into a browser cell in the form of a table with six columns. The columns are for the name of map sheet, the creation date, points, features, arcs and text. The points column is subdivided into two columns: a type, which is the TRIM attribute code, and a set of markers. These markers are further subdivided into centre, rotate, x-scale, and y-scale. Centre is divided into x, y and z. Features are the core data for network models. They are divided into 2 sub-cells labeled type and geometry. Type is the TRIM attribute code and geometry is a list of 3-D points in North American Datum (NAD) 83, Universal Transverse Mercator (UTM) projection. We transform these 3-D points into polyline features for C&E. According to the TRIM specification, the first point in each polyline is the most upstream point and the last point is the most downstream point. A seamless polyline of edges requires that the last point of an upstream edge be identical to the first point of the downstream edge that it connects to. The third step is to modify the TRIM data to suit our model. Although most of the TRIM stream data is connected and clean, there are instances where data inconsistencies appear. For example, the TRIM data that describes the Fraser River Basin crosses three UTM zones with the vast majority in zone 10 (Fig. 7). The ellipsoid nature of the earth causes some distortion from North to South when the data is projected onto a plane.

The distortions become more significant when we transform the data from zones 9 and 11 to zone 10 to build a seamless network of the Fraser. A detailed discussion can be found at http://cartes.mcan.gc.ca/basics. When we modify the TRIM data to correct these inconsistencies, we leave the original data intact and archive the modifications separately.

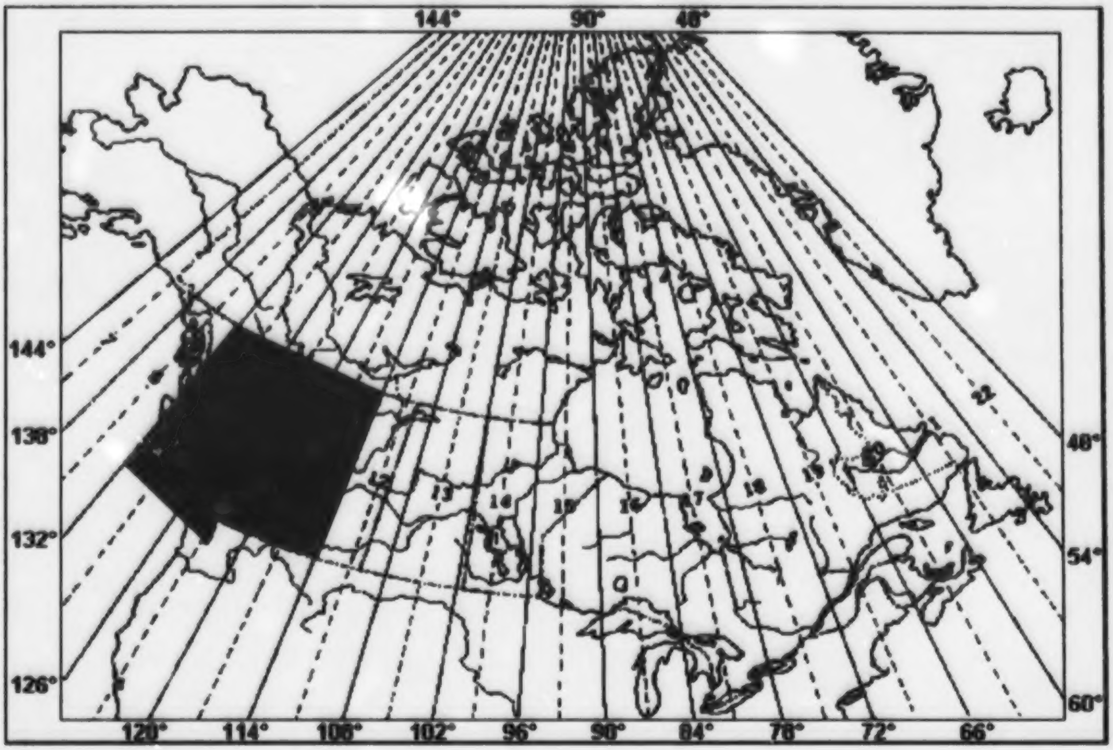


Figure 7. Universal Transverse Mercator zones for Canada, with Fraser River TRIM data in zones 9-11.

The network builder process detects several inconsistencies in TRIM data that require modification before the network is suitable for modeling migration paths for salmon:

- Water bodies in the TRIM maps do not necessarily exist as connected data. TRIM data is defined from a land-centric point of view, as the title of the maps suggests. Consequently, if a stream enters a culvert, for example, it disappears from the map. A similar effect, where a river becomes unconnected, almost always occurs across UTM zones. Moreover, in many cases, there are gaps between map sheets, possibly caused by the UTM transformations.
- Edges are assigned the wrong TRIM code. For example, a left bank is assigned the TRIM code for a right bank.
- Edges are digitized in the wrong direction. For example, a river is digitized in an upstream direction instead of a downstream direction or a lake is digitized in an anticlockwise direction instead of in a clockwise direction.
- A line or a point is unexpectedly duplicated.
- Some minor tributaries connect to the wrong watershed.
- Lakes do not form closed polygons.
- Construction edges between rivers and lakes are missing one of the two edges or a third construction edge appears in the data.

The Department of Computer Science at the University of B.C. in partnership with Facet developed functions for diagnosing and constructing networks in C&E. Table 2 summarizes the key functions.

Table 2. Key functions used to create a network.

FUNCTION	USE
create_network	Create the connections and topology between network edges.
upstream	Return the set of network edges upstream from one network edge. Useful for identifying the set of stream edges that are considered part of one watershed.
connect_edge	Connect the downstream point of one edge to the upstream point of another edge to close a gap in a stream edge or to connect two networks together.
delete_edges	Delete unwanted edges from a network
reverse_edge	Reverse the direction of an edge in the network.
open_boundary	Locate edges where the geometric interpretation of the edge does not match its current configuration in the network. For example, find lake edges that have one end not connected to another lake edge, which implies that the lake is not a closed polygon.
downstream	Return the set of network edges downstream from one network edge. Useful for identifying the mainstem of a river.
collapseAll_Index	Create a centerline for 2-line rivers and lakes. Maintain an index from the centerline edges back to the lake shore and riverbank edges.
section_network	Subdivide the edges of a river's mainstem into equal-length edge spans.
connect_network	Connect networks into a larger network.

3.3.2. Net Corrector Model

The Net Corrector model is the first model that created a network. The operator uses the model to define the TRIM data that is needed to complete a stream network and to define the extent of the watershed. The stream edges are automatically extracted from the TRIM database and converted to polylines for viewing. The operator begins with a simple form (Fig. 8) and an overview of the available networks shown as polymarkers (Fig. 9). Watershed names become visible as the user zooms in to a small area in the visualizer (Fig. 10).

A new network is started by defining a Stream Information Summary System (SISS) stream, starting with the map sheet that contains the most downstream points for the mainstem river in the watershed. The operator places a polymarker (+) at the most downstream point of a single line stream or at the downstream points of both the left and right banks of two-line rivers by selecting the downstream edge(s) in the visualizer. The model automatically finds the selected edge(s) in the TRIM data and identifies the most downstream xyz point. The operator identifies the most upstream points on the mainstem in the same way. The xyz locations of the downstream points are inserted into a database by clicking the "Selected edges are Most downstream" button (Fig. 11). The stream code used in SISS,

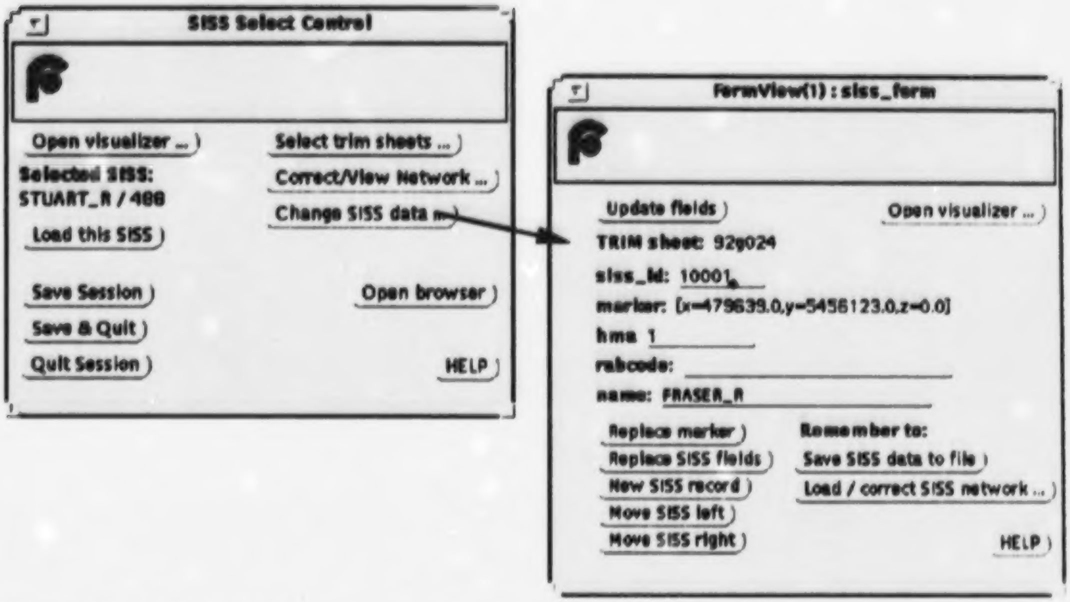


Figure 8. Forms used in Net Corrector for a new network or maintenance of a network.

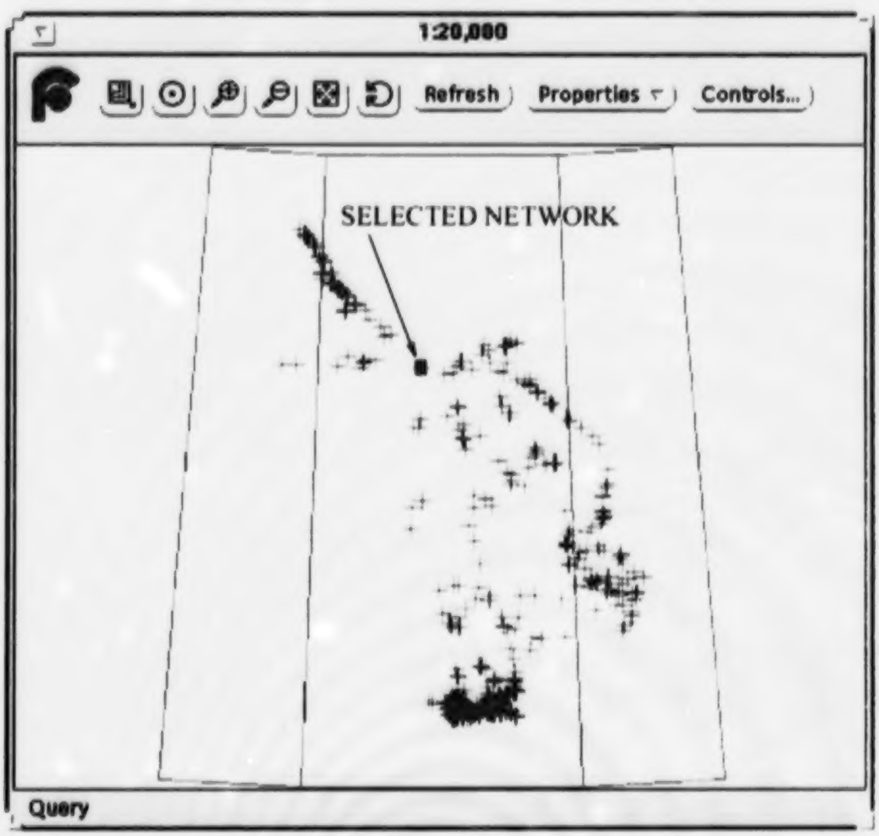


Figure 9. Polymarkers indicating existing watershed networks with UTM zones.

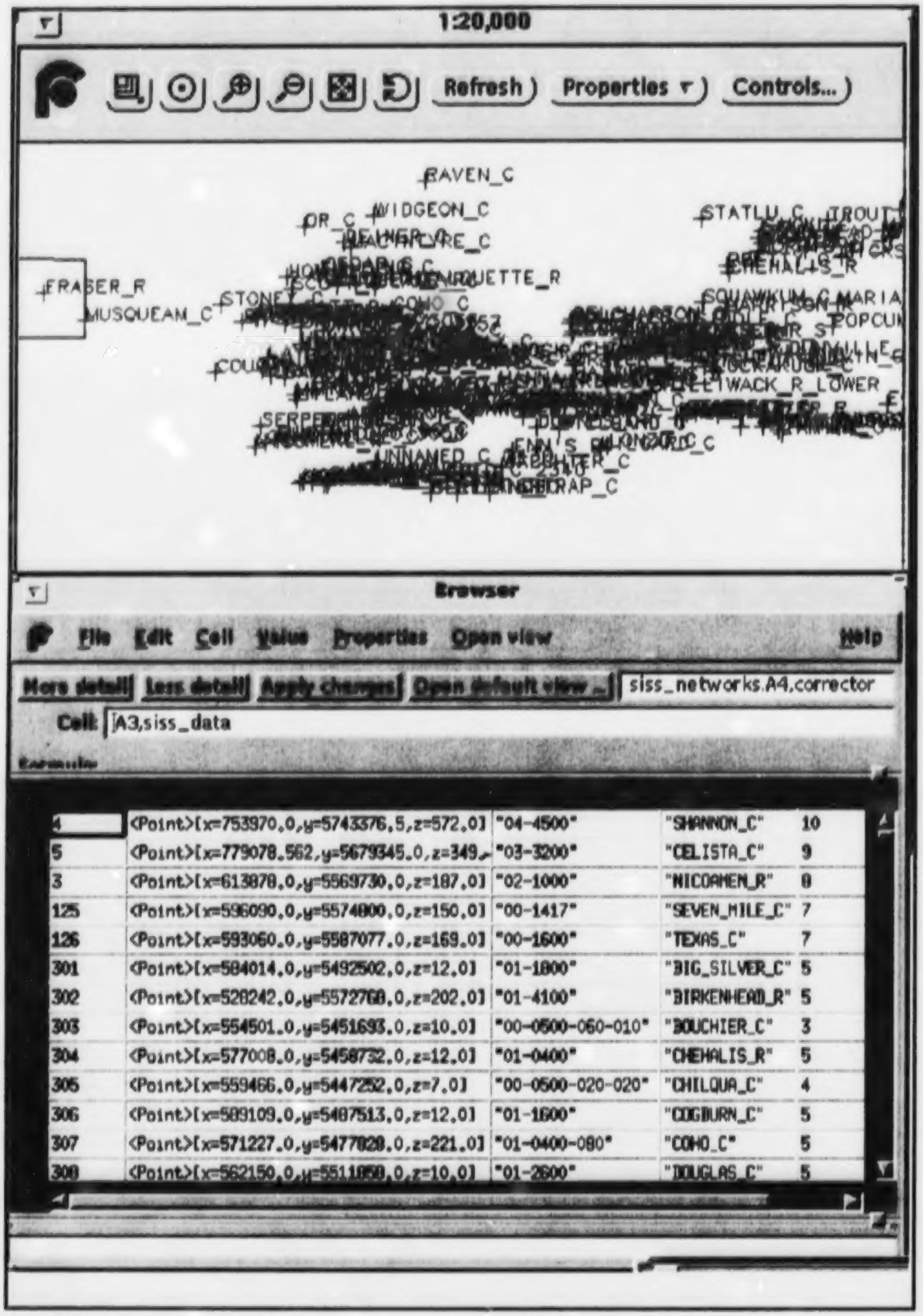


Figure 10. Watershed polymarkers with watershed names and the associated database.

Rabcode, the Stream Name, and the Habitat Management Area (HMA) code are all entered into the same form. Clicking the "Select new SISS/Change data" button adds the new SISS's record to the database (Fig. 11).

Clicking the left mouse button on a polymarker selects an existing network from the database. The "Load this SISS" button loads the data and displays the network to be edited with polymarkers and name (Fig. 11). If the network needs more map sheets, the operator can click the right mouse button in the visualizer at the location where no data is displayed and the model will see if the required TRIM sheet is available on the workstation. If the sheet is available then it can be added to the watershed using the "Add more Trim" button on the model's GUI. The model finds the edges that are connected to one another in the watershed's TRIM sheets and then finds all the edges that are upstream from the watershed's most downstream points. The model overlays the upstream edges on the TRIM sheets in a visual to show the operator the upstream edges that are connected to the downstream points. The unconnected TRIM edges are displayed in yellow (Fig. 12). In this model each edge displays an arrowhead (Facet feature) at its the most downstream point to indicate its direction (Fig. 12). Unconnected edges can be snapped together while edges that "flow" in the wrong direction are easily reversed using the GUI interface (Fig. 11).

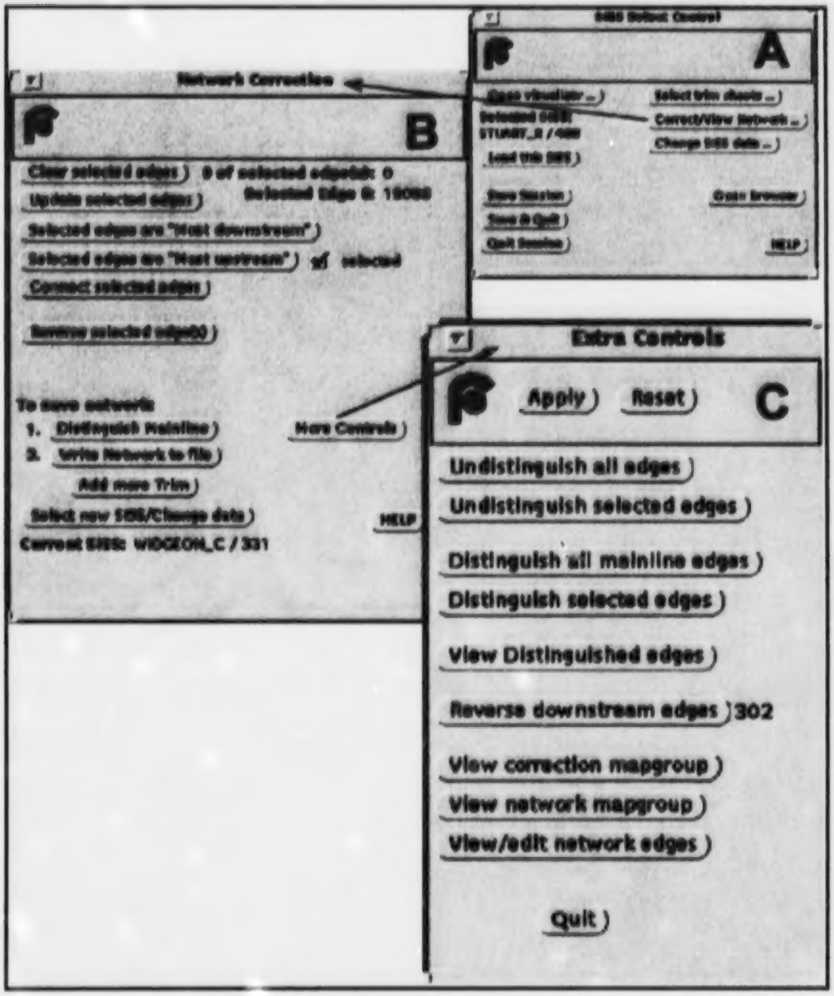


Figure 11. Form **A** is used to start editing. Form **B** and **C** are used for editing network data.

We built networks for all the salmon spawning streams in the Fraser Basin using this model. The model could trace a migration path from the spawning grounds to the mouth of the Fraser using the downstream function. The path followed the right or left bank of the rivers, single lines, and lake edges. We could easily calculate slope, which is a key habitat parameter for salmon (Hubert and Kozel 1993), and distance from these paths (Fig. 13).

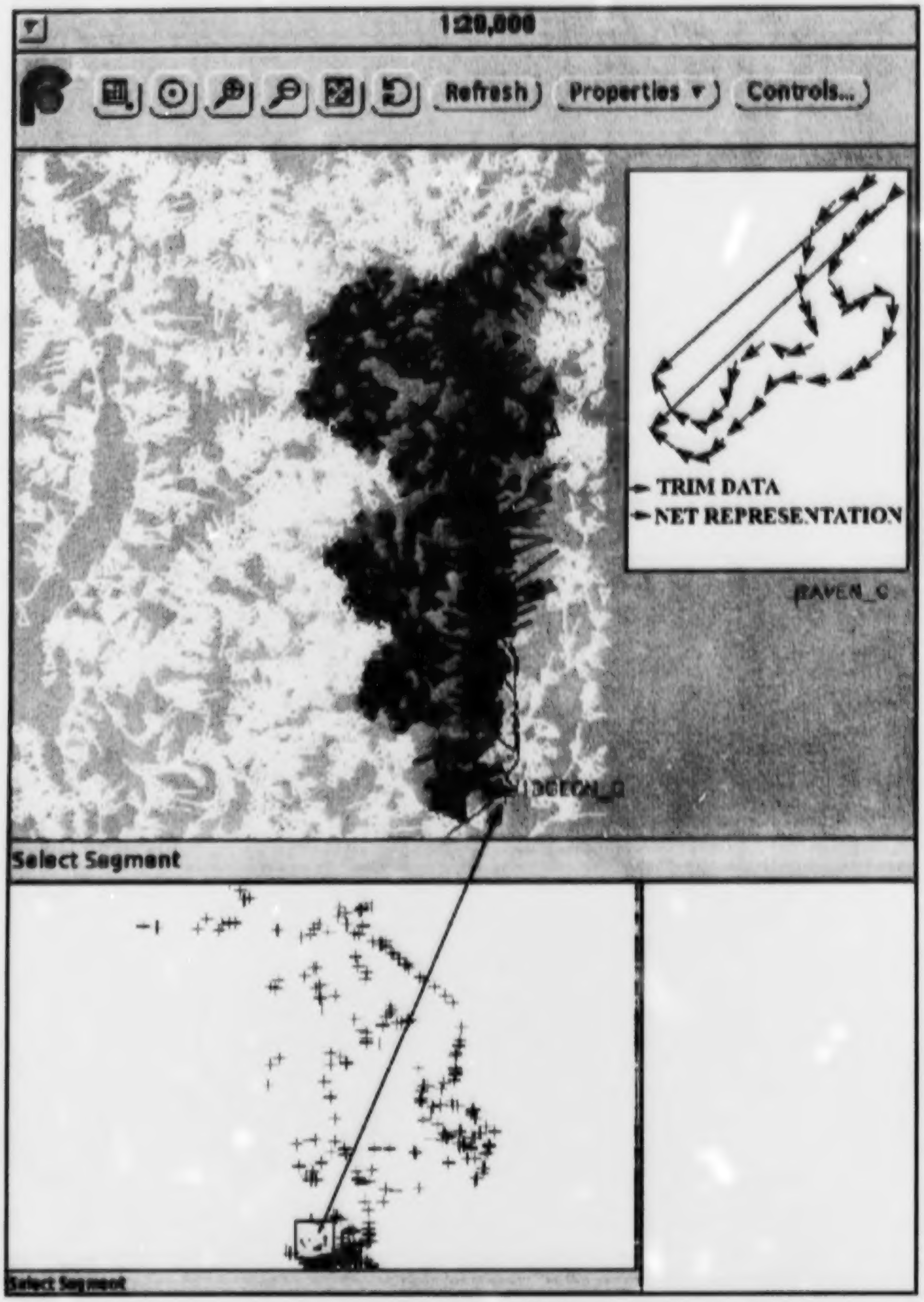


Figure 12. Example of a map image of TRIM data (Widgeon Creek) used in Net Corrector.

Unfortunately, the paths in these networks were not good approximations for the salmon migration paths that needed to cross lakes. The paths traced the lake edge in a clockwise direction, which can introduce significant errors especially in the distance calculations. In some cases, several hundred kilometers were added to migration paths. For example, the Horsefly River salmon migration path traces

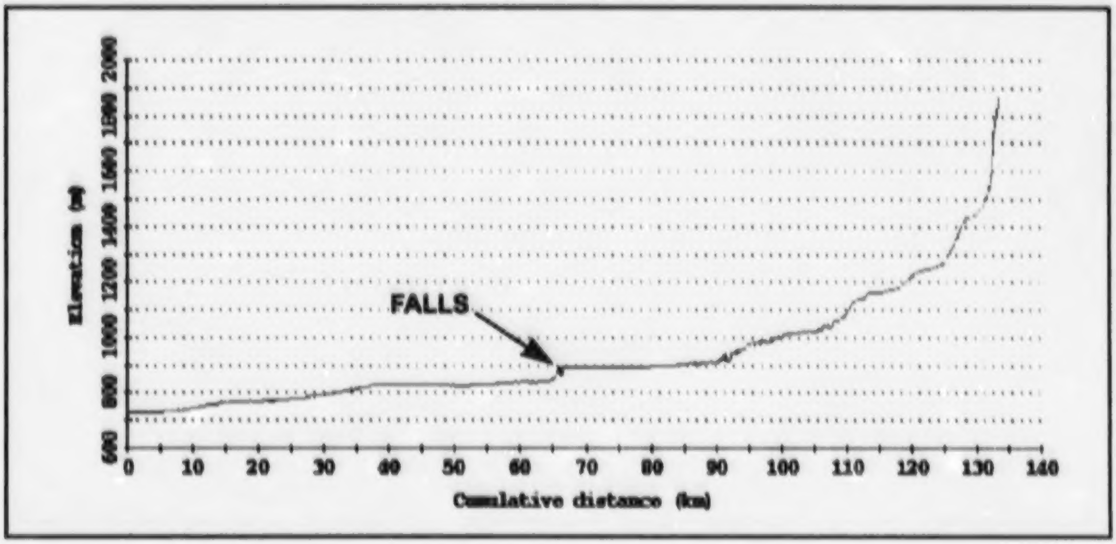
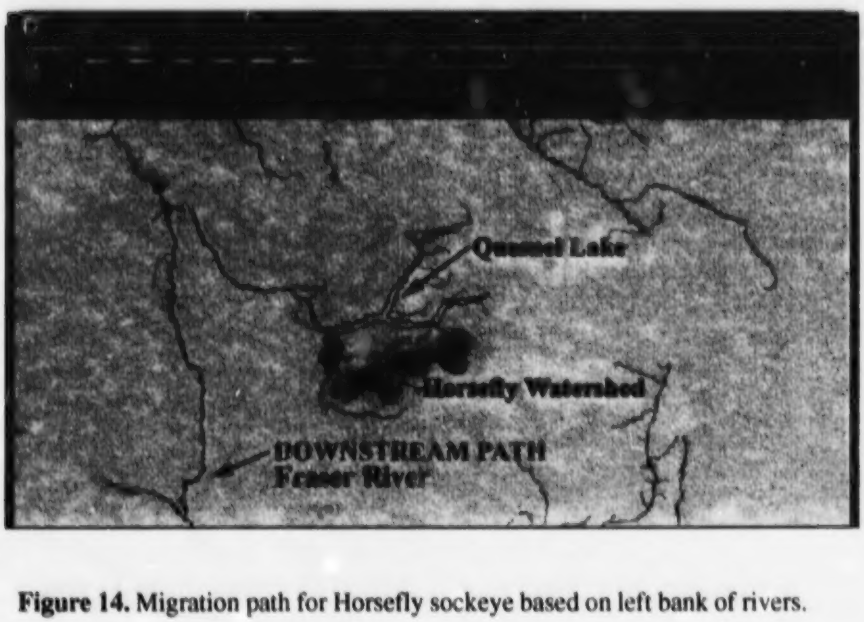


Figure 13. Elevation profile for the migration path of Horsefly sockeye in the Horsefly River.

the shore of Quesnel Lake to the outlet and branches continuing around the lake as well as down the Quesnel and Fraser rivers (Fig. 14). In addition, the elevation of a riverbank is sometimes well above the water. This occurs in canyons and often along the outside bank of a bend in the river. These elevations, while not accurate on a small scale or in areas of canyons, provided a reasonable overview of slope. Improvements to the representation of river slope could provide better data for more detailed analysis of salmon habitat.



In the hope of reducing the distance inaccuracies, we chose to create a new model that would generate a centerline through two-line rivers and lakes while maintaining its connectivity to all tributaries. The new model is described in Section 3.3.4.

Figure 14. Migration path for Horsefly sockeye based on left bank of rivers.

3.3.3. Net Updater Model

The Net Updater is an intermediate model that transfers data from the Net Corrector model into the Mainline Extractor model. It has a single GUI interface in which the operator enters the SISS file names from the Net Corrector model and the output file name for a network that is suitable to the Mainline Extractor model.

The Net Updater reads the list of TRIM mapsheets, the upstream and downstream points of the mainlines, and the archived modifications from the Net Corrector model's output. The model applies the modifications to the TRIM data and constructs the interconnections between network edges. The model stores the resulting network along with the mainline upstream and downstream points in a file for the Mainline Extractor model as a "raw" network (Fig. 15).

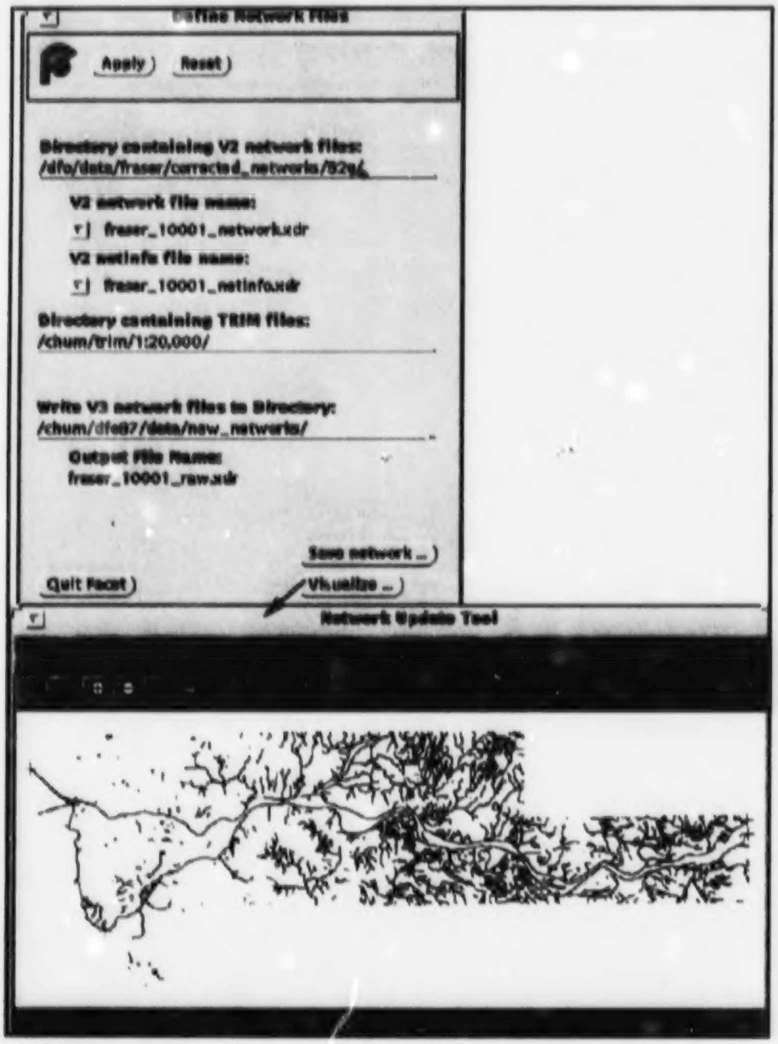


Figure 15. Form used in Net Updater model and associated image.

3.3.4. Mainline Extractor Model

The Mainline Extractor model has two goals: to allow the operator to correct inconsistencies in the data and to compute centerlines for rivers and lakes. The operator accesses the model through a GUI interface. The GUI provides many of the functions available in the Net Corrector model, but also includes a function to change edge "kind", the ability to add a line by digitizing on screen, and the collapse function for calculating centerlines (Fig. 16). The function that calculates centerlines of a network relies on the geometric properties of the TRIM data in the network. Consequently, the Mainline Extractor Model may require modifications to the TRIM data beyond what was done in the Net Corrector model.

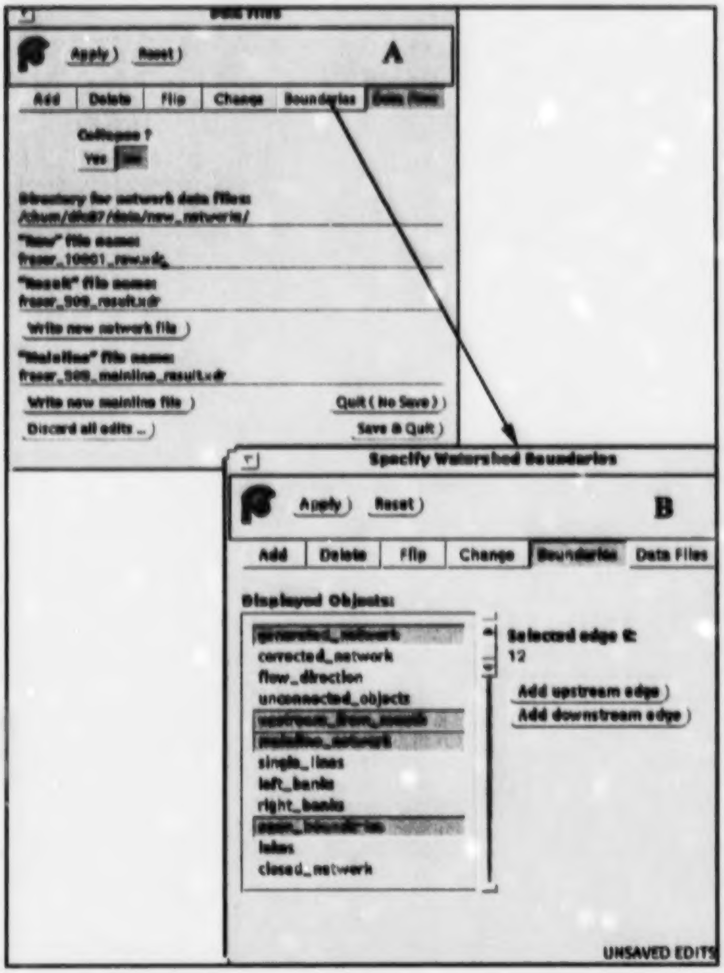


Figure 16. Mainline extractor forms.

In the first of two steps in the Mainline Extractor model, the operator cleans the network data that is supplied by the Net Updater. The cleaning process involves the same steps as in the Net Corrector: reverse edges, add edges, removed edges, and change edge attributes. The collapse function also requires that no points or lines be duplicated in the network. For example, all of the construction lines, which are pairs of lines in opposite directions that close off the mouths of rivers, must be removed before the network can be collapsed. This model automates much of the interactive processing of the Net Corrector. It automatically detects reversed edges, unconnected lines inside the network, and construction lines. Despite the automation, some problems still require an operator to correct them.

The GUI for the Mainline Extractor offers several diagnostic functions to the operator. The operator can find problem areas by selecting a number of display formats in the "Specify Watershed Boundaries" form (Fig. 16). These formats include a view of flow directions for edges, upstream edges from the watershed mouth, the river mainline (downstream), and open boundaries (used to check for broken networks) (Fig. 17). The last format, open boundaries, reports edges whose connections within the network are inconsistent with the TRIM specification. These edges are typically mislabeled edges or a sequence of reversed edges.

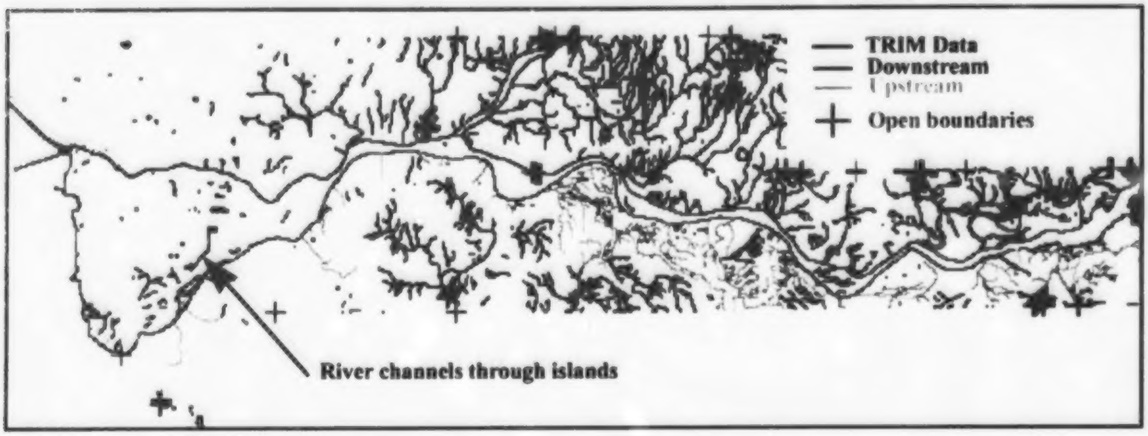


Figure 17. An example of a map in the Mainline Extractor model, the lower Fraser River. The right bank is broken as indicated where the blue turns to black.The black tributaries are also disconnected.

In the second step in the Mainline Extractor model, the user selects the "Collapse" option in the GUI and the model creates centerlines for the rivers and lakes in the network. The collapse function triangulates each lakes and two-line rivers to identify opposite riverbanks or lakeshores. Every triangle that is adjacent to a tributary is temporarily marked. The function identifies a set of triangles that link all the marked triangles to one another within one river or lake and marks the triangles in the set; the marked triangles limit where the centerline will go. Next, The function then constructs a centerline by connecting points between neighboring marked triangles. Finally, the function returns the centerlines, triangles, and index between triangles and the river banks that border the triangles as a centerline network called an "indexed network" (Fig.18). While the indexed networks are represented as single lines, they retain an association. The centerline networks give a better representation of the migration path for salmon, provide surface area estimates for two line rivers and lakes, and improve slope calculations for the rivers. Improved estimates of surface area proved useful in calculating heat transfer in the IOS Fraser

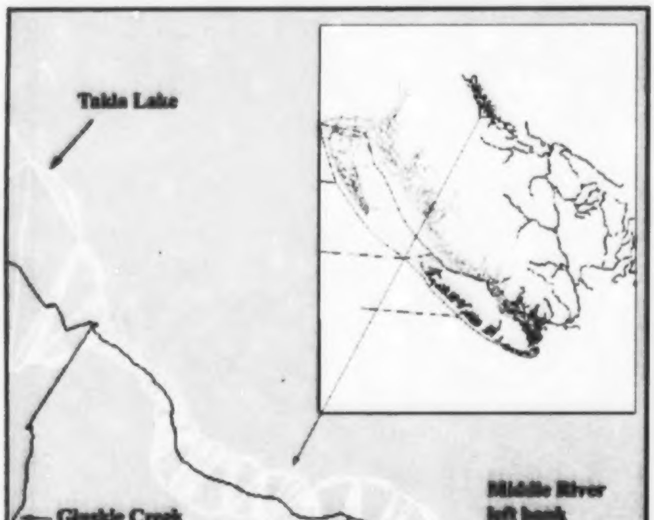


Figure 18. Example of a mainline network showing Middle River, Takla Lake, and tributaries with associated TIN data.

After the centerline networks are created, we structure the networks in one more way to align them with external data. For example, the Fraser River Temperature Forecasting model data outputs are for 67 sections of the main-stem Fraser from Hope to Shelley, each identified as 10 kilometers long. Similarly, the Nechako-Stuart migration path for Early Stuart sockeye is divided into 45 - 4.7 km sections. The function called "section_network", breaks a river network's edges into any number of equal-length sections between two points or edges. We use this function to create the 67 sections in the mainstem Fraser from Hope to Shelley and the 45 sections in the Nechako-Stuart networks.

Over the course of this project, 149 functions were built in C&E for using or building networks (appendix a). Two UBC libraries for C&E, ubcnet (for networks) and ubcvor (for Voronoi-related functions), contain all the functions. Information about the functions appears in the C&E help menu.

4.0. FRASER RIVER BASIN NETWORKS

Mainline networks with centerlines were constructed for the mainstem Fraser River and its major tributaries as well as 125 watersheds in the Fraser Basin that have been identified as salmon producers. These are stored as individual units that can be connected into larger watersheds as needed. The longest centerlines are the migration paths for salmon spawning populations.

4.1 Migration Path

Location	Easting	Northing	Elevation	Distance to mouth of Fraser River, km	Slope * 1000
Fraser River	487490	5443700	0	0	
Pitt River	516447	5451988	1	48	0.021
Mission	551555	5442091	5	89	0.098
Hope	612314	5471244	34	167	0.372
Qualark Creek	613686	54488510	43	186	0.474
Hells Gate	611585	55515645	84	219	1.242
Thompson River	600894	5565983	145	275	1.089
Seton Creek	575862	5614875	200	334	0.932
Bridge River	575365	5622502	206	343	0.667
Chilcotin River	541506	5732197	351	483	1.036
Quesnel River	533408	5868956	470	640	0.758
Westroad River	508485	5906875	509	699	0.661
Nechako River	518766	5974366	569	809	0.545
Stuart River	464504	5982353	631	872	0.984
Bowron River	577288	5991368	604	910	0.347
Ft. St. James	417453	6033226	680	992	0.402
Tete Jaune	737445	5875089	735	1218	0.425

The migration path network for the Early Stuart Sockeye stock group contains over thirty individual watershed networks. These sectioned networks were connected using a function called "connect_networks" to create one large continuous network from the Queen Charlotte Islands to the mouth of the Fraser River to the spawning streams in the Stuart-Takla region (Fig. 19). This network provides a spatially explicit stream network with hundreds of thousands of points available for attaching attribute data. Key locations in the network can be added to a database by selecting a location

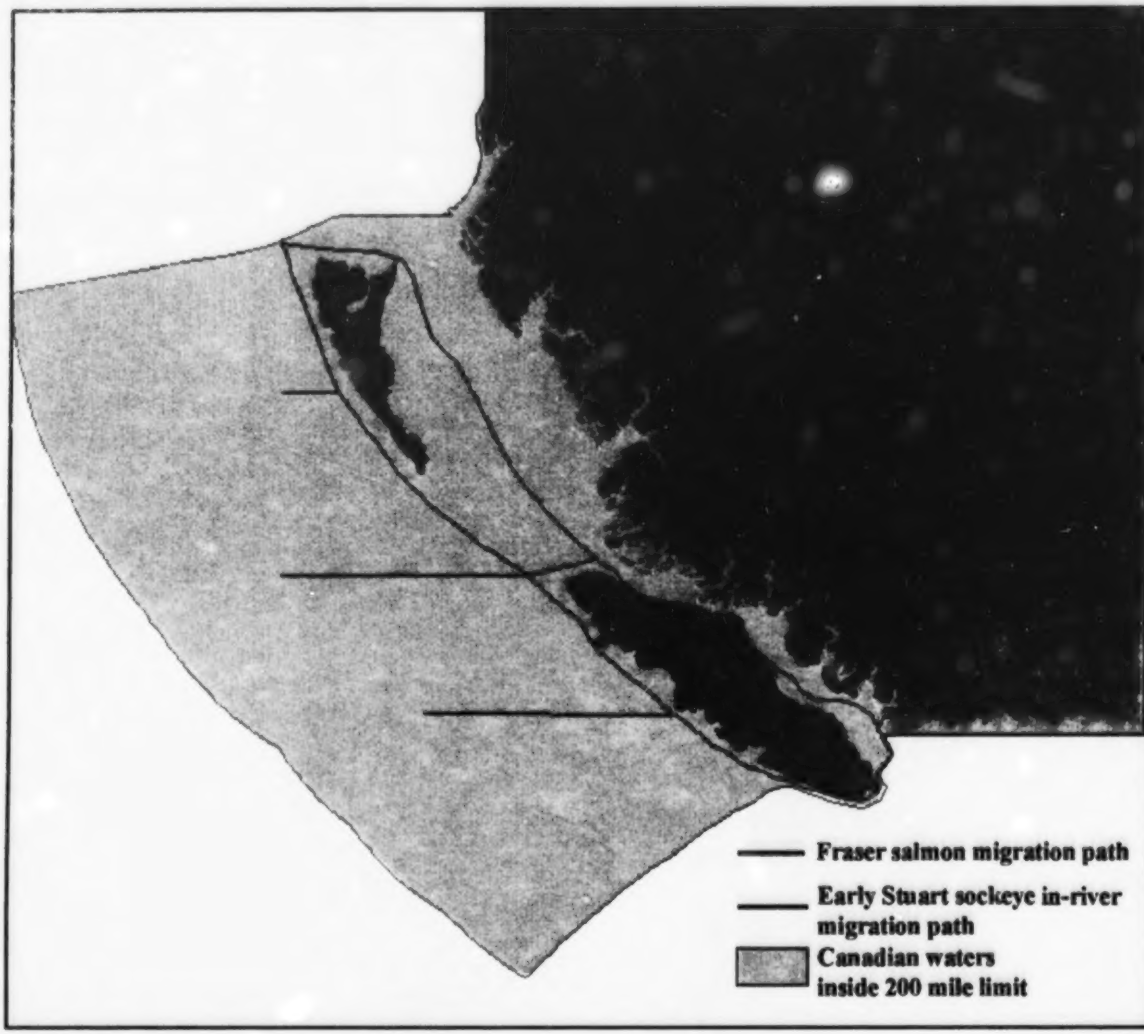


Figure 19. Early Stuart sockeye stock group migration network.

on the map or by editing the database manually. Key locations used in the Early Stuart network are summarized in Table 3, including location, elevation above mean sea level, distance to the mouth of the Fraser and slope between locations. These features can also be used in other migration networks. The Early Stuart spawning streams attached to this network, the location of the mouth of the stream, its elevation above sea level, and distance to the mouth of the Fraser River are summarized in Table 4.

4.2. Spawning Locations

Spawning locations within spawning streams are taken from the descriptions provided in the SISS publications. These are transferred to xyz points on our map base using another model called Fraser Harvest and Migration. A GUI called concept builder is developed to enable non-experts to create relatively sophisticated models. A database, key_location_streams, is created for the catch and spawn locations using this GUI. Location labels are retrieved from the escapement database and a blank

Table 4. Location of sockeye spawning streams based on UTM coordinates normalized to zone 10, elevation above sea level, and distance to the mouth of the Fraser River from the mouth of the streams in the Early Stuart network.

Stream Name	Easting	Northing	Elevation	Distance to Fraser mouth
Sowchea Creek	409242	6031746	680	992
Pinchi Creek	404869	6046436	682	1009
Tachie River	385791	6058571	682	1026
Kuzkwa Creek	378973	6072732	685	1045
Middle River	364088	6081937	691	1068
Kazchek Creek	360279	6084947	692	1075
Baptiste Creek	356873	6087273	687	1079
Sidney Creek	347782	6073587	691	1086
Paula Creek	346529	6073045	691	1087
Fleming Creek	344710	6071786	691	1088
Van Decar Creek	350117	6093800	687	1091
O Ne-ell	346881	6097221	687	1095
Forfar Creek	342218	6102394	687	1103
Gluskie Creek	339390	6103936	688	1107
Casimar Creek	336922	6106643	688	1111
Bivouac Creek	335941	6106282	688	1111
Leo Creek	335105	6107438	688	1113
Sandpoint Creek	329874	6111960	688	1121
Sakenichie	323559	6115239	688	1128
Narrows Creek	326817	6117031	688	1139
Shale Creek	326846	6129008	688	1140
Blanchet Creek	325020	6128791	688	1142
MacDougall River	309092	6124620	688	1146
Point Creek	310952	6124510	688	1146
Fifteen Mile Creek	324589	6135161	688	1148
Hooker Creek	309661	6130499	688	1154
Sinta Creek	307720	6132604	688	1154
Crow Creek	308705	6131638	688	1154
Dust Creek	307713	6133471	688	1157
MacLaing Creek	314217	6149839	688	1165
Hudson Bay Creek	311714	6152634	688	1169
Frypan Creek	306134	6157372	688	1177
Forsythe Creek	305203	6159612	688	1180
Ankwill Creek	299214	6172586	688	1193
French Creek	300716	6172619	688	1194
Bates Creek	296597	6178242	688	1200
Driftwood	295665	6177393	688	1201
Blackwater Creek	294810	6178168	688	1202
Lion Creek	288620	6185878	707	1222
Porter Creek	287227	6185932	710	1224
Kotsine River	281907	6191315	712	1240
Kastberg Creek	273960	6201666	745	1259

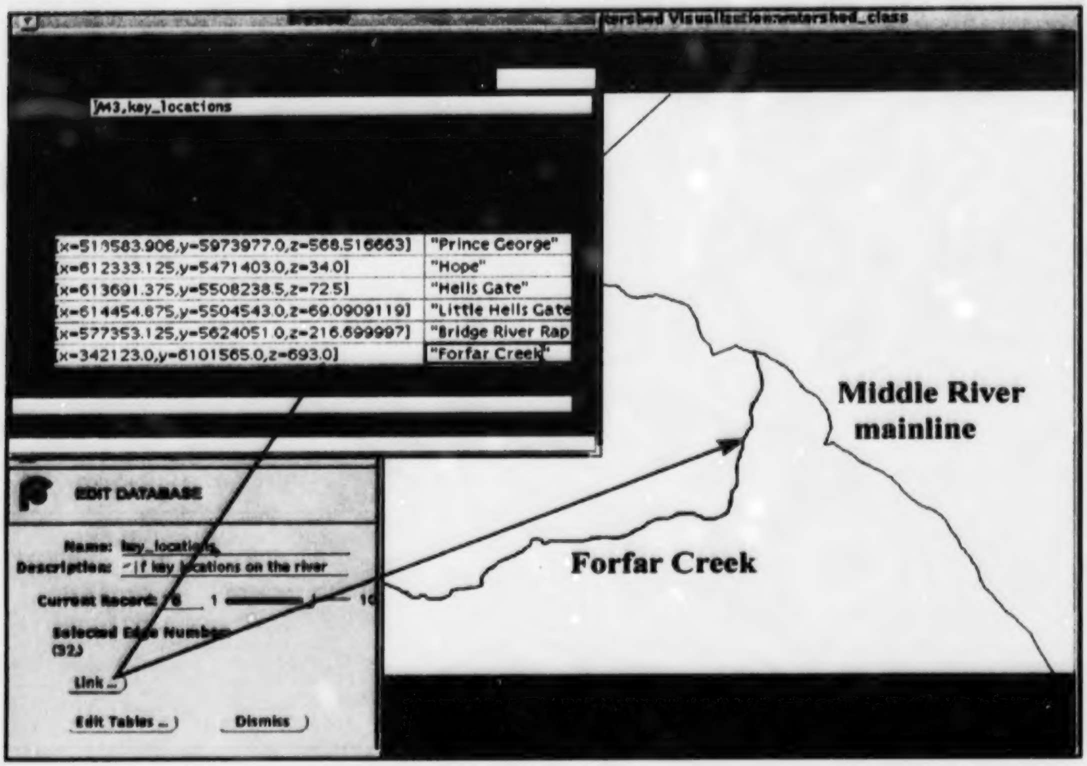


Figure 20. Example of an interactive tool to add explicit spatial data to a location selected on-screen.

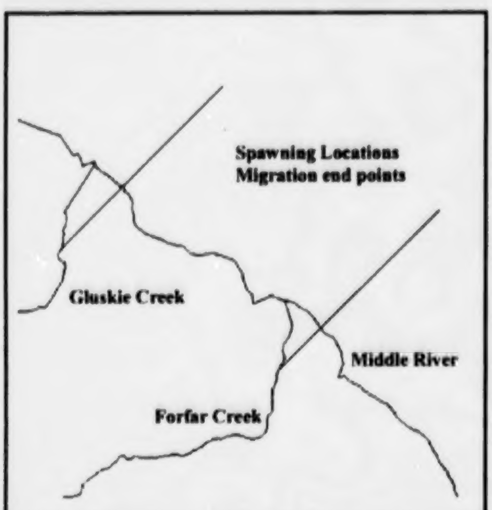


Figure 21. Spawning locations with 20-km segments used as migration end points in the IFSaM migration model.

column was created for the locations. A link function associated with the edit database function is used to populate the database, with xyz locations picked on-screen from the Early Stuart network (Fig. 20). To complete the migration path we attach 20-km segments to the spawning locations as migration end points (Fig. 21). This is accomplished using a function labeled partition_at_point. The appropriate edge is partitioned at a point representing the mid-point of the spawning location. A 20-km segment is then joined to the network, reaching skyward at a 45^{0} angle in order to differentiate these from stream surfaces. These 20-km segments are necessary when modeling many populations within a stock group, all with identical timing. In these cases, each population must have a unique location that defines the end of the migration as there are situations

where a spawning location for one population is in the path (downstream) of another.

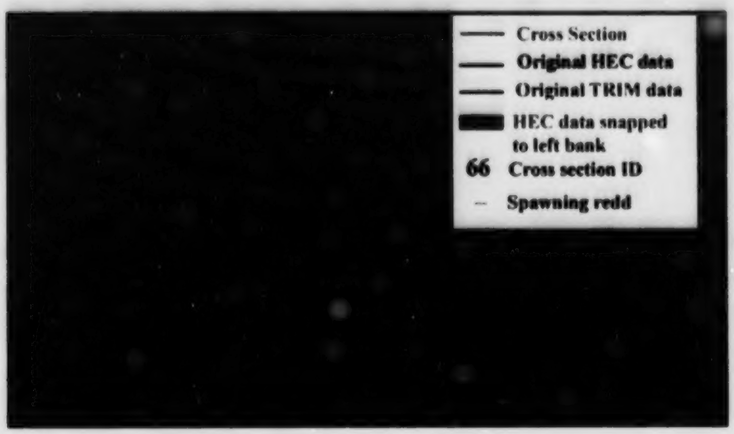


Figure 22. Nechako network partitioned with spawning locations.

Stream networks can be ordered in C&E so that the user can display a network by selecting stream orders. This is dependent on the network, so that in a migration network that starts at the Fraser River mouth, first order spawning streams in a single watershed will be 3rd or 4th order streams in a system of connected watersheds.

Another example of adding detail to a base network is the Nechako River network used in the Nechako Chinook Life History Model. Detailed data from the Nechako Fisheries Conservation Program is attached to the 1:20,000 base and the network is partitioned at key locations. Individual chinook spawning locations (redds) were also added (Fig. 22). In addition, cross sectional data from a survey of the Nechako River was added to the network. River depth was interpolated from cross section data and the resulting left edge of the interpolated data was forced to the left bank of the river providing a surface for the river bottom (Fig. 22).

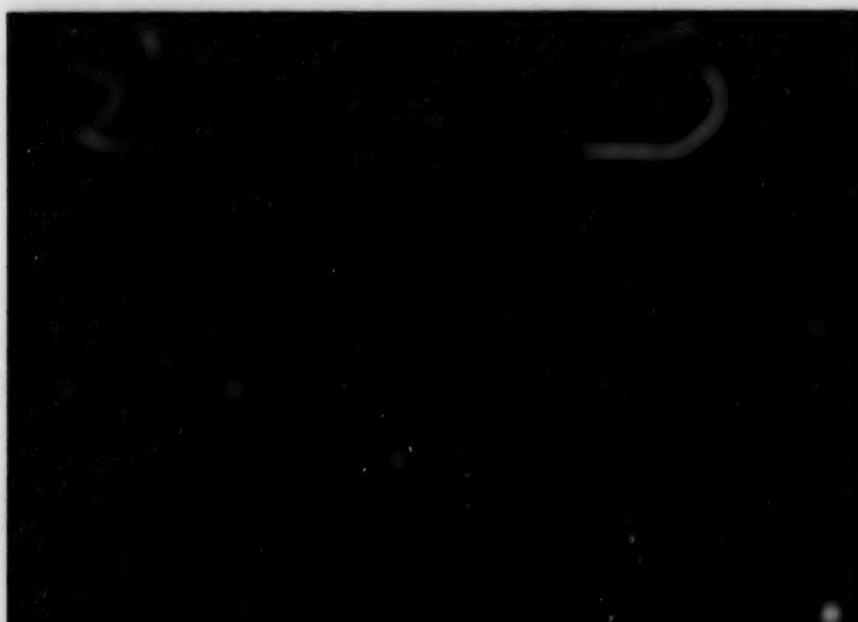


Figure 23. Horsefly River TIN network with slope categories designated by colour.

TIN networks can be generated for land using DEM data, thus enabling estimates of slope for features next to a river or lake. This was demonstrated using 27 TRIM map sheets from the Horsefly watershed. Included in this image is a display of river slope categories over the 125 km length of the river (Fig. 23). The red areas represent the lowest slope.

Figure 24. Calculated drainage paths from a simulated hillside disturbance in a 3D TIN network.

unsuitable for sockeye spawning. The blue areas represent the steepest slopes, also unsuitable for spawning. The yellow and green areas represent potential spawning areas. These surfaces can be connected to our networks to provide a modeling platform for land use impacts to streams and lakes. An example of this is a triangulated irregular network (TIN) surface of a watershed with simulated hillside disturbances. The drainage path is estimated from the disturbance location and the aspect of the triangles in the TIN network. These drainage paths connect to the watershed network to form a seamless link, useful for analysis of downstream effects (Fig. 24).

Spatially explicit networks are a useful base for linking fish production to habitat, harvest, and the community, especially if the networks are flexible and easily adapted to external data. The networks we build in Facet Decision Systems C&E software are both flexible and adaptable. The tools were developed over a period of three years and are currently capable of dealing with the many "anomalies" in TRIM data that hamper the creation of centerline networks. Both external data and models can be attached to these networks with relative ease providing a powerful, spatially explicit base for modeling physical, biophysical and biological processes.

5.0. ACKNOWLEDGEMENTS

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7.0. APPENDIX

7.1. Networks: Facet Optional Library (ubcnet - Beta documentation)

connected_component	Finds all edges that are connected to one given edge
create_network	Creates a basic network from a list of points
delete_edges	Deletes edges that do not form part of the network
detect_disconnected	Finds edges within a specified tolerance
detect_reversed	Finds edges with incorrect direction / flow
downstream	Finds all edges that are downstream of a selected edge
fuse	Joins two edges in a network
_index	Finds the line in a network closest to a point
keep_edges	Keeps edges that form part of the network
match_origin	Finds directed edges with a selected point of origin
nonmonotonic	Finds edges that flow uphill
polyProjectionArea	Finds the area enclosed by a polygon
reverse_edges	Reverses selection order to correct flow direction
shatter	Converts polylines into segments
simplifyPolyline	Generalizes Polylines in a network
strahler_order	Orders the edges in a network
suspect_reversed	Finds nodes with multiple edges flowing out of them
upstream	Finds all edges that are upstream of a selected edge

7.2. TINs: Facet Optional Library (ubctin - Beta documentation)

area	Area of a polygon or TIN
copy_z	Creates z values for points in a TIN
down_to_net	Finds a list of network edges through a network.
drape	Drapes a list of points on a TIN
face_elevation	Finds the average height of vertices in a polygon
find_triangle	Finds the directed edge that contains a given point
flood_for_watershed	Finds the watershed for a river network
include_line	Includes polylines into a TIN
left_face	Finds the triangle on the left side of an edge
name_rivers	Groups a list of edges together and gives it a name
path_down_to_net	Finds a path through a TIN following the surfaces
pits	Finds the lowest points in a TIN
ridge_edges	Finds all the ridges in a TIN
ridge_valley_edges	Finds all ridges and valleys in a TIN
tin_edges	Finds the edges that form a TIN
tin_faces	Finds the triangle faces in a TIN
trickle_down	Finds the flow down a TIN from a list of points
up_to_ridge	Finds the flow up a TIN from a point
valley_edges	Finds all valley edges in a TIN
vertex_anglerange	Finds vertices with x-y plane/TIN edge angles within a given range
vertex_degrees	Finds adjacent edges to vertices
watershed_boundaries	Determines watershed boundaries in a TIN

7.3. Voronoi: Facet Optional Library (ubcvor Beta documentation)

closeBoundary	Creates a closed network within a boundary
closeBoundary_Index	Creates a closed network within a boundary and returns indexed network structure
collapseAll	Collapses a network
collapseAll_Index	Collapses and Indexes a network
deindexTable	Updates an attribute list of floats after indexing a network
findAreaFeature	Finds all lakes and double-line rivers in a network
findBadCycles	Finds cycles with problems
findBoundaryIncon	Finds boundary inconsistencies
findConstruction	Reduces construction edges in a network
findCyclesThatArent	Finds cycles that should be open features
findDoubleEdges	Locates pairs of edges with the same start and end points
findFigure8	Finds network edges that twist together
findInsideOutLake	Finds lakes with inconsistent edges
findIsolatedEdges	Finds miscellaneous edges that are not part of the network
findIsolatedLakes	Finds lakes that do not form part of the network
findOpenBoundary	Finds edges of lakes and double rivers that have no connections
findRiverInLake	Finds rivers that run through lakes from digitizing
findSingleBoundaries	Finds edges from double rivers that do not belong to the network
findUnexpectedCycles	Locates unusual cycles in a network
floatToQuadTable	Creates a table of float values for a list of edges
intToQuadTable	Creates a table of integer values for a list of edges
limitedWalk	Checks connectivity in a network
qedgePathToPointList	Interprets quad edge lists
traceMedial	Finds all connected edges with matching characteristics

7.4. Facet UBC Optional Libraries: Beta Notes (unsupported)

Assumptions

These functions have mainly been tested with TRIM data. Some problems have been reported when using them with lat/lon data. The scale and error separation that we assumed for the TRIM data is different for lat/long data. Comments and notes are also specific to how TRIM data is digitized according to the BC 1:20 000 digitizing specification. Other forms or sources of digitizing may differ in how they handle construction edges or what happens when double sided rivers meet each other or meet a lake.

Definitions

Cycle

A cycle is a sequence of one or more edges that leads back to the edge you start with. A cycle should surround some bit of area. Note: these two notions can conflict - going around the outside of a lake satisfies the first definition but it wouldn't normally be considered as an enclosed area (unless the area is wrapped around a point at infinity). If you generally accept the notion of an "enclosed area", then it will work. The term is a common definition in graph theory.

Display all of the closed polygons in a network;
This task is broken up into two steps.
First, find all the edges that are involved in the closed polygon. To imagine this, put your right hand on an edge and pretend that all the edges are walls. Now walk around the inside of the polygon until you're back to where you started. The sequence of directed edges forms a list of all the edges of the polygon, ordered around the polygon.
Second, create one big polygonal line that goes around the polygon. The edgePathToPointList function completes this. The sequence of qedges has a first edge. This is where the path starts. Assume that these paths are cycles. Start with the second point of the first qedge and start going around the polygon. When the last qedge in

the path is reached, the last point of this last qedge is added to the sequence of points. This last point of the last edge should be the same as the first point of the first edge and all of the points are included. When the path isn't closed, all of the points are still returned. The function looks at the first point of the first qedge and the last point of the last qedge. If they're different, then the feature is a path rather than a cycle. The path then re-includes the first point, effectively starting with the first point of the first qedge instead of starting at the second point of the first qedge.

Quad Edges

Quad edges form the basis of entire networks. They are the same as qedges or directed edges. Direction is the only way of identifying a closed feature from another. Normally when you see a polygonal line, we see a line. In the UBC code, we actually see four things at once:

1. two directed lines (one going in each direction)
2. and two fictional lines that go to the polygons on each side of the line.

Each of the directed lines and each of the fictional lines is called a quad edge. These four views that UBC sees are then bundled together into something called a quad. So, a quad is essentially the same thing as a polygonal line. Only the UBC internal code, and maybe some debugging functions, should ever see quad edges (sometimes called qedges) or quads. The UBC functions should return indexes into a list of polygonal lines.

qedge = quad edge = directed edge
quad = edge = undirected edge

Pairing of edges

The function starts with all the open edges of the rivers and lakes (as returned by findOpenBoundary). It selects one edge and starts following the polygon boundary on the left side of the edge. Whenever it reaches another open edge, the function assumes that it has travelled all around the lake or double sided river and creates a construction edge between its starting point and where it ended up. Hopefully, this explains why the edges that findSingleBoundaries returns are a problem for this routine.

Note: you should run *closeBoundary* before removing construction edges from a network. Construction edges sometimes help make lakes look smaller or help to avoid some problems. For instance, you have a lake that is cut off at one mapsheet boundary and a double line river that feeds into the lake.

Warning! When the river is cut by another boundary, then removing the construction edges between lake and river before running ***closeBoundary*** **will create paths from one mapsheet boundary to another (along the banks), and the closing algorithm will join up the wrong ends.**

CollapseAll functions

Network assumptions that the function needs. It assumes that:

1. lake and double river polygons are closed
2. the areas to collapse are formed only by lake or double sided river edges

Tributaries

Tributaries are identified as any edge entering a vertex on the boundary of the lake or double sided river that isn't part of the lake's interior. When there are two identical lines along the boundary of a lake (e.g. two construction lines between a lake and a double sided river) and the construction lines aren't removed, then the collapsing function assumes that there are two tributaries coming into the lake. The collapsing function then extends both banks of the double sided river into the collapsed lake. This can look a bit odd when you first see it and don't have an explanation for it.

findDoubleEdges

When the vertices aren't identical all along the way then they won't be detected as double edges. We do this so that lakes that only have two edges as their lake shores aren't necessarily pegged as being doubled up.

Warning! The down side is that, on a rare occasion, you might get two construction edges that may not match up perfectly on one vertex. As a consequence, you don't find these mismatched construction edges.